Astrophysical jets & high-energy particles: Toward a full self-consistent description of particle acceleration

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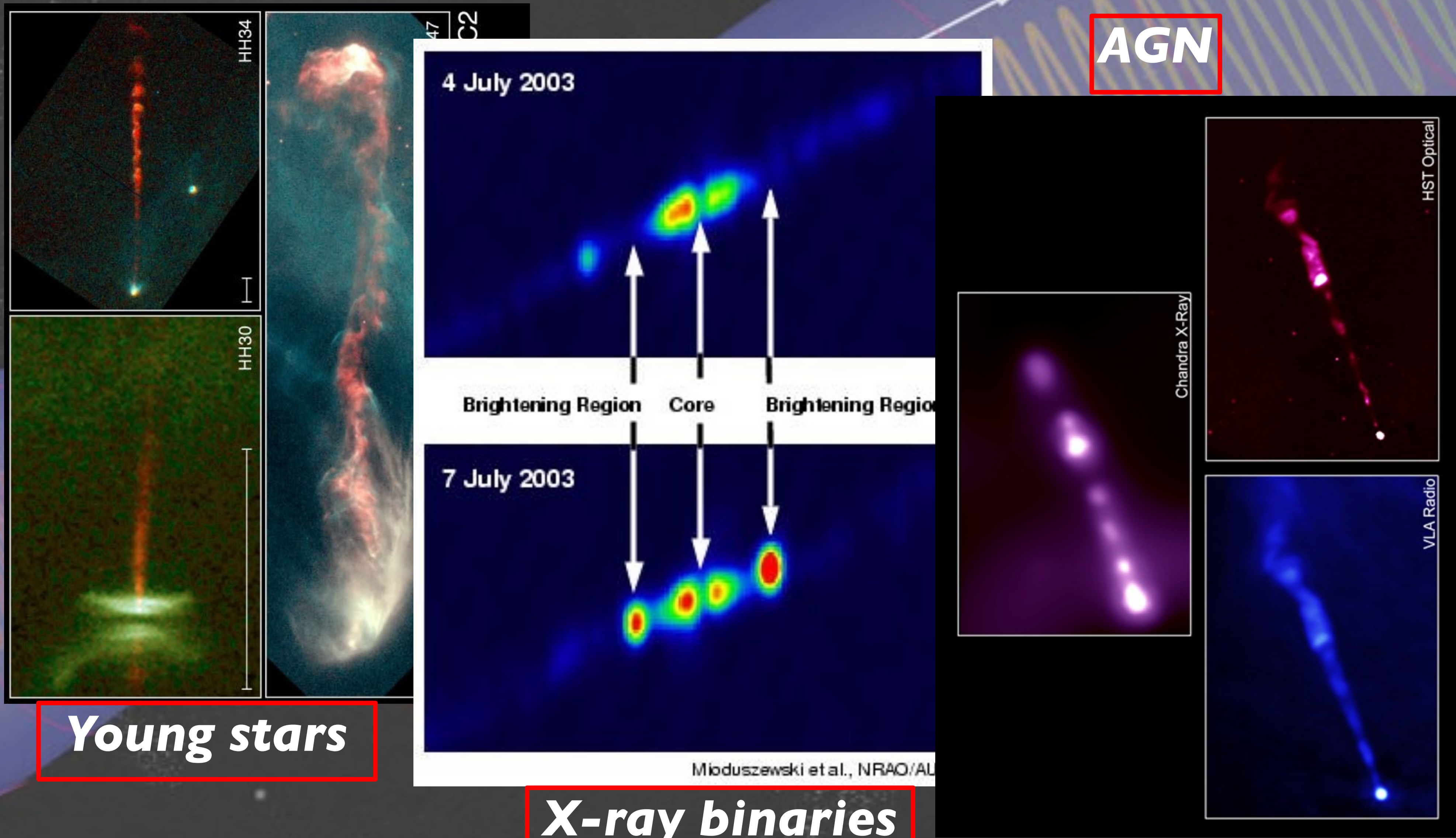
Astrophysical jets in the Universe

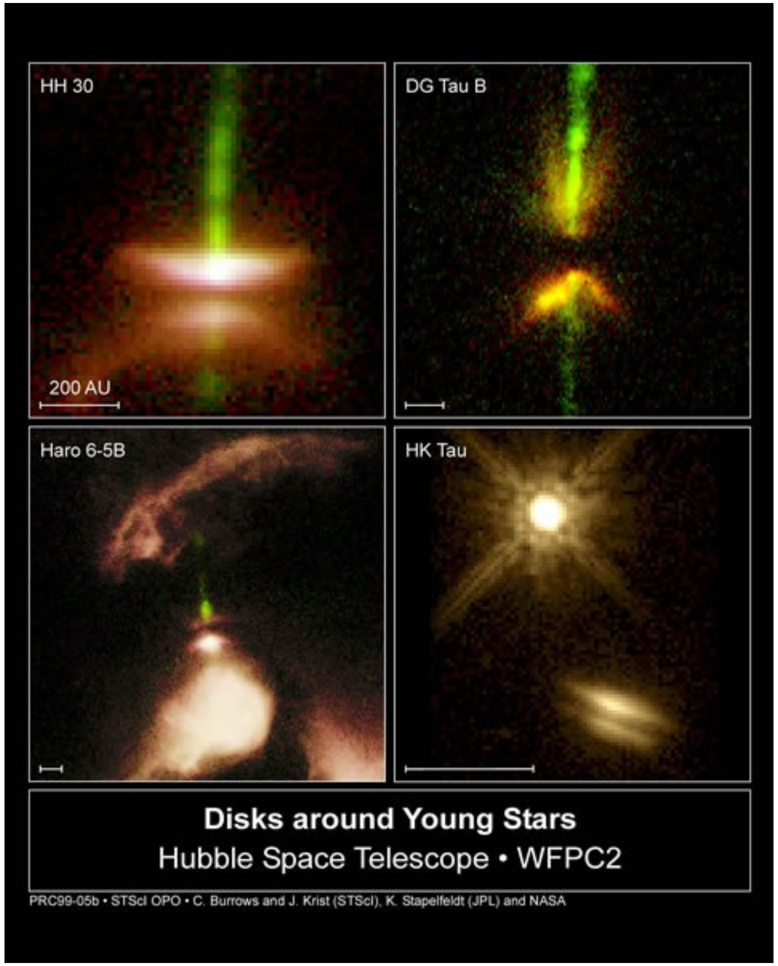


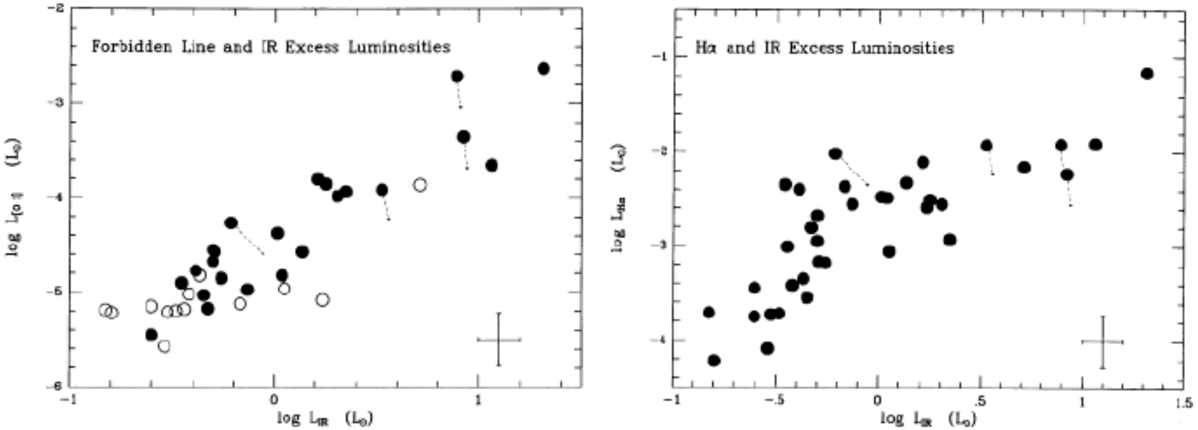
Young stars

X-ray binaries

AGN

Young stars and jets

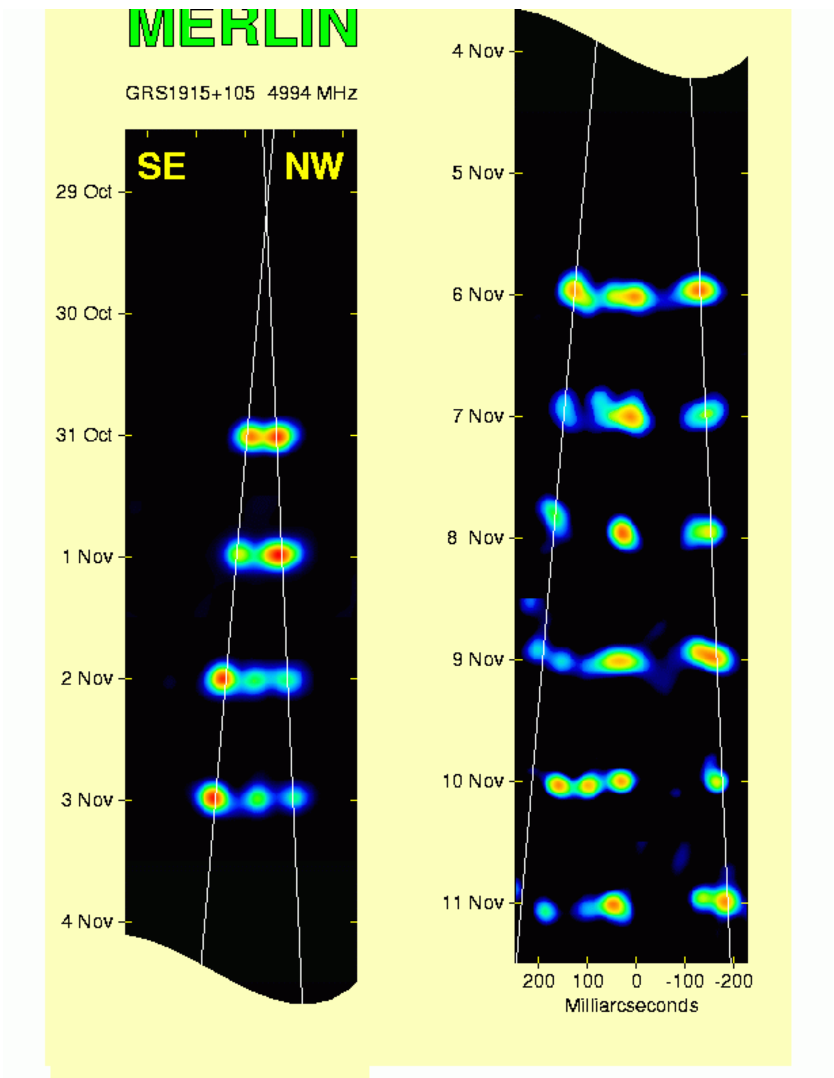


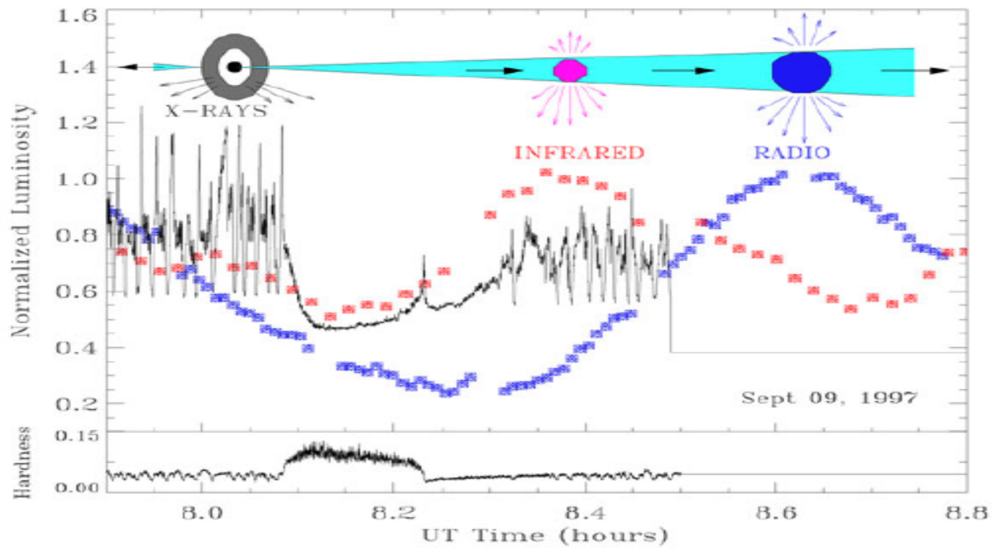


Cabrit et al. (1990)

- Size of the jets $>10^3 - 10^4$ AU.
- Jet velocity up to ~ 600 km/s.
- Correlation between jet radiative emission and disk luminosity.
- Detection of several components within the jet (e.g. Dupree et al'05).

Jets in X-ray binaries

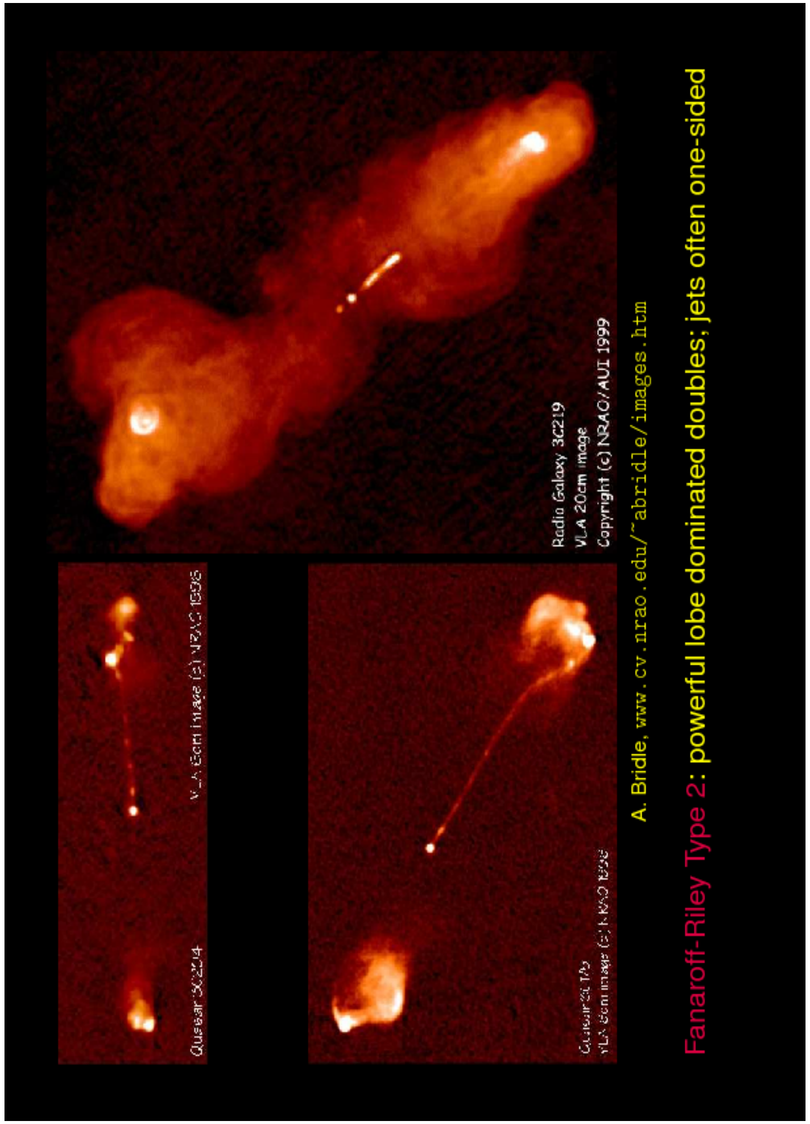


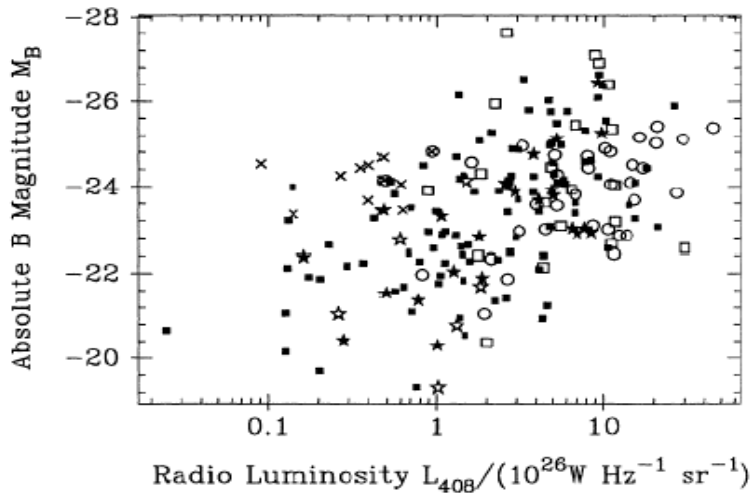


Mirabel et al. (1998)

- Size of the jets ~ few hundreds of AU
- Jet velocity up to 0.95c .
- Correlation between disk luminosity and jet associated emission.

Jets in Active Galactic Nuclei

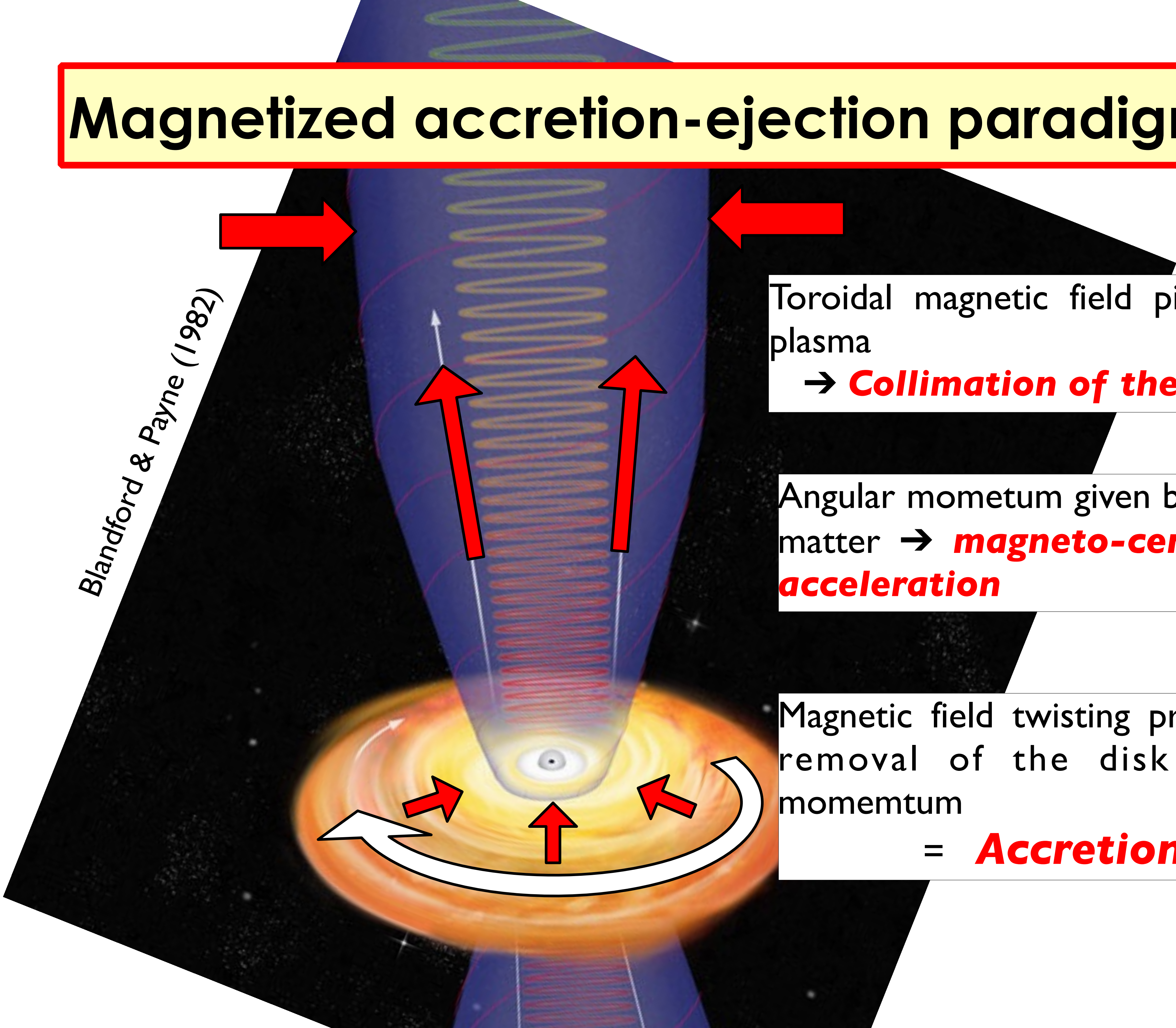




Serjeant et al. (1998)

- Size of the jets of a few Mpc.
- Several components within the jet (FR2).
- Jet velocity up to $\Gamma_{\rm bulk}$ ~10 (pc scale) with a slower enveloppe.
- Correlation between disk luminosity and jet associated emission.

Magnetized accretion-ejection paradigm



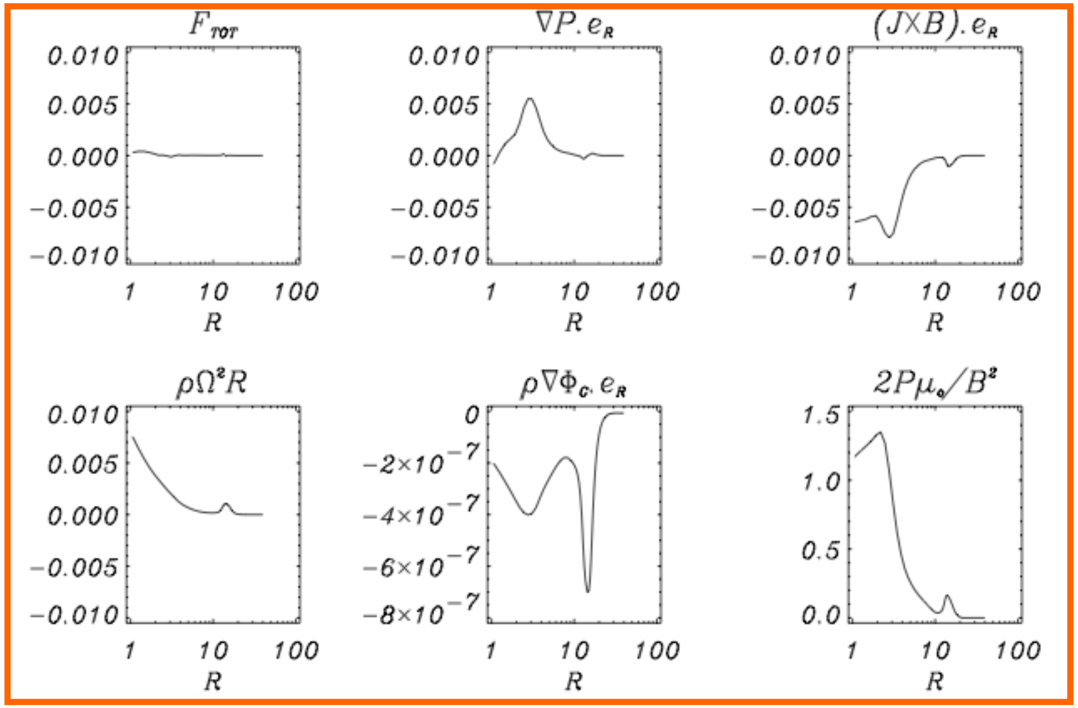
Toroidal magnetic field pinches the plasma
→ ***Collimation of the jet.***

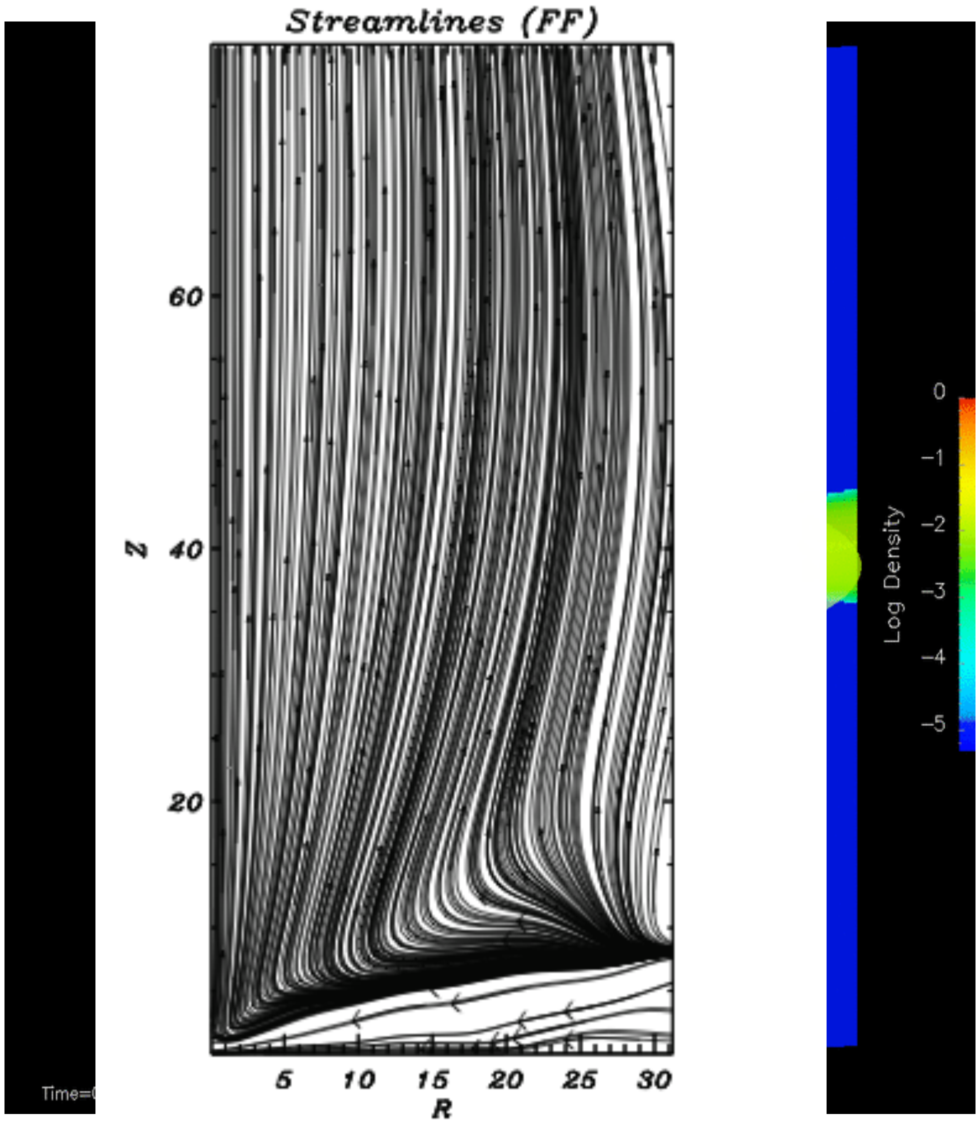
Angular mometum given back to jet matter → ***magneto-centrifugal acceleration***

Magnetic field twisting provoked a removal of the disk angular momemtum
= ***Accretion***

MHD simulations of accretion disks launching jets

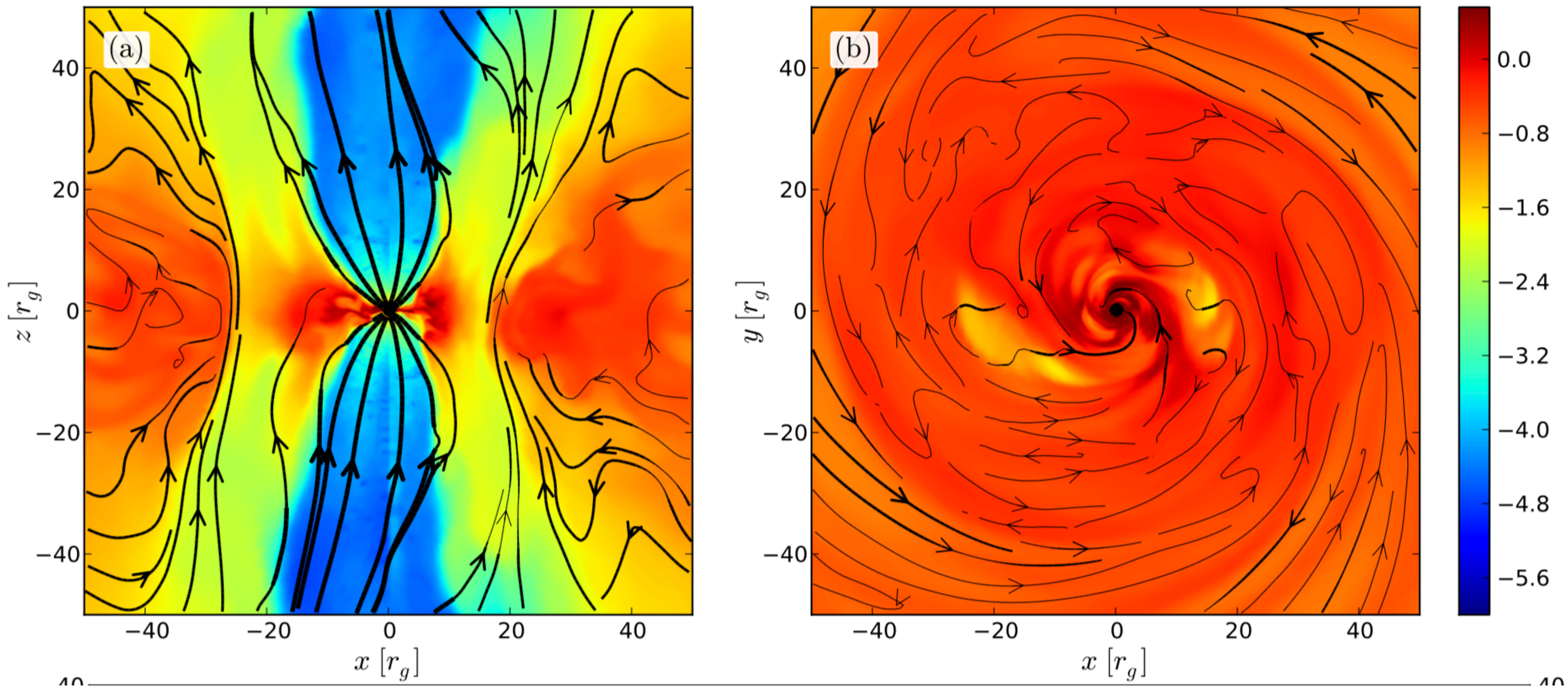
- Casse & Keppens (2002,2004) presented the first MHD simulations showing an accretion disk launching *steady* jets.





GRMHD simulations of accretion disks launching jets

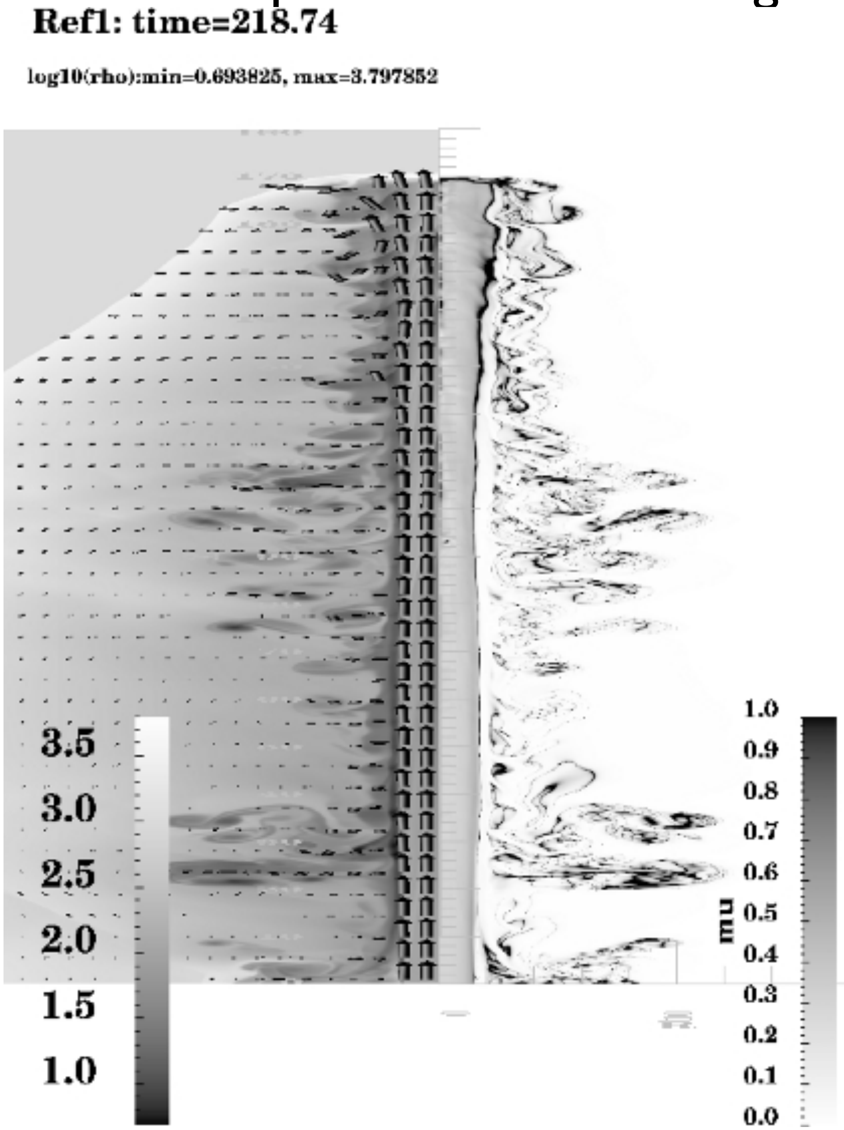
- In the last decade, GRMHD codes have been able to partially depict outflows launched from black-hole/accretion disks systems:
  - ➡ Jets are highly time-dependent because of the Ideal GR-MHD paradigm.
  - ➡ Inner jets are mainly Poynting dominated outflow.

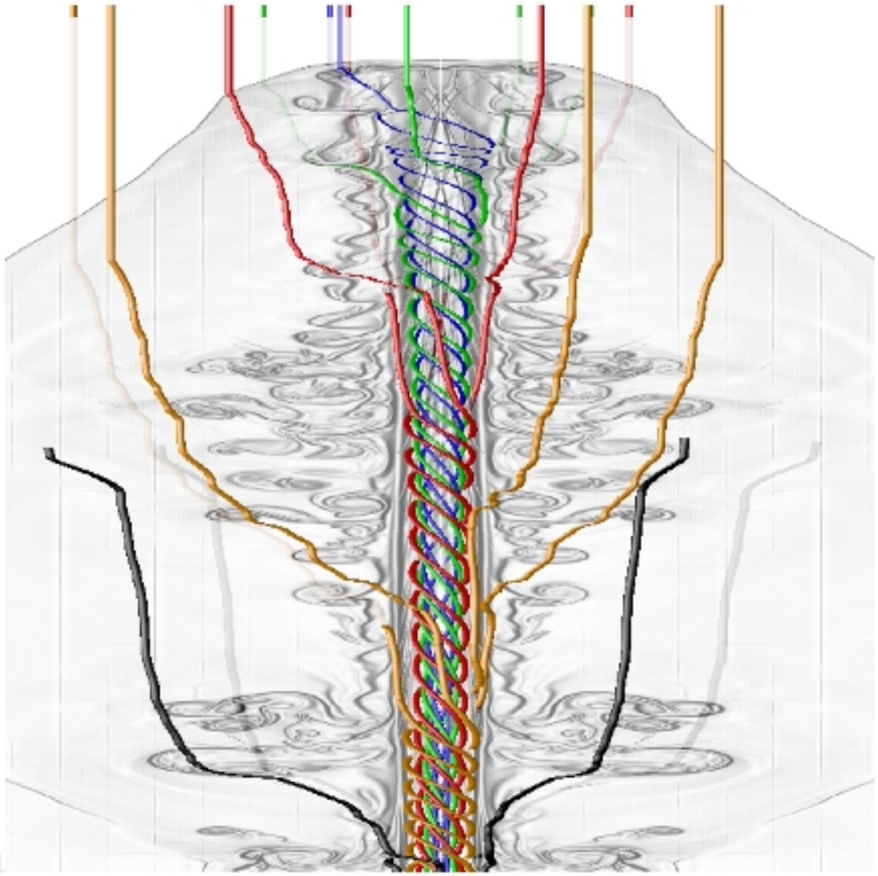


Tchekhovskoy & McKinney (2012)

Astrophysical jets propagation : non-relativistic MHD vs relativistic MHD

⇛ The shape of the surrounding cocoon varies from NR to R MHD jets.





RMHD jet (Γ_{bulk}~8)

Keppens et al. (2008)

Astrophysical jets propagation : Velocity of the terminal shock

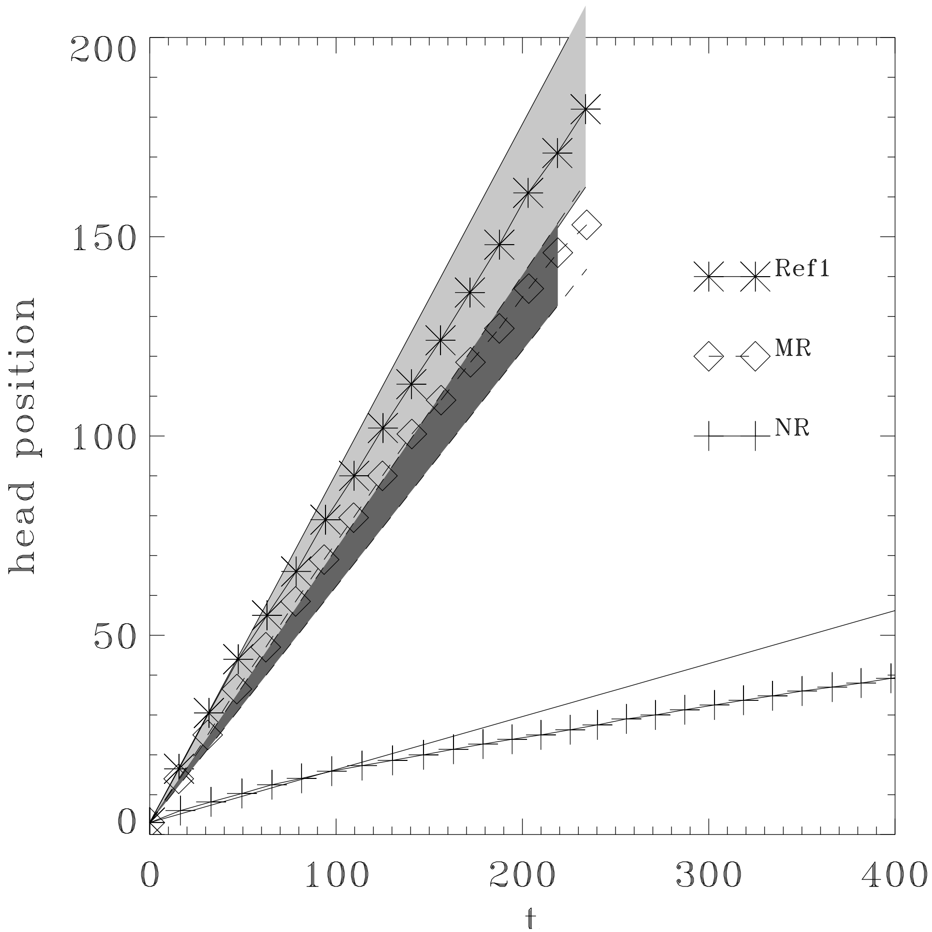
⇛ Relativistic jet propagation with toroidal magnetic field

$$V_{head} = \frac{\sqrt{\xi_b/\xi_a}}{1+\sqrt{\xi_b/\xi_a}} V_z$$

⇛ Formula for RHD jets (Marti et al. 1997)

where ξ_b is the relativistic enthalpy of the beam while ξ_a is the enthalpy of the ambiant medium

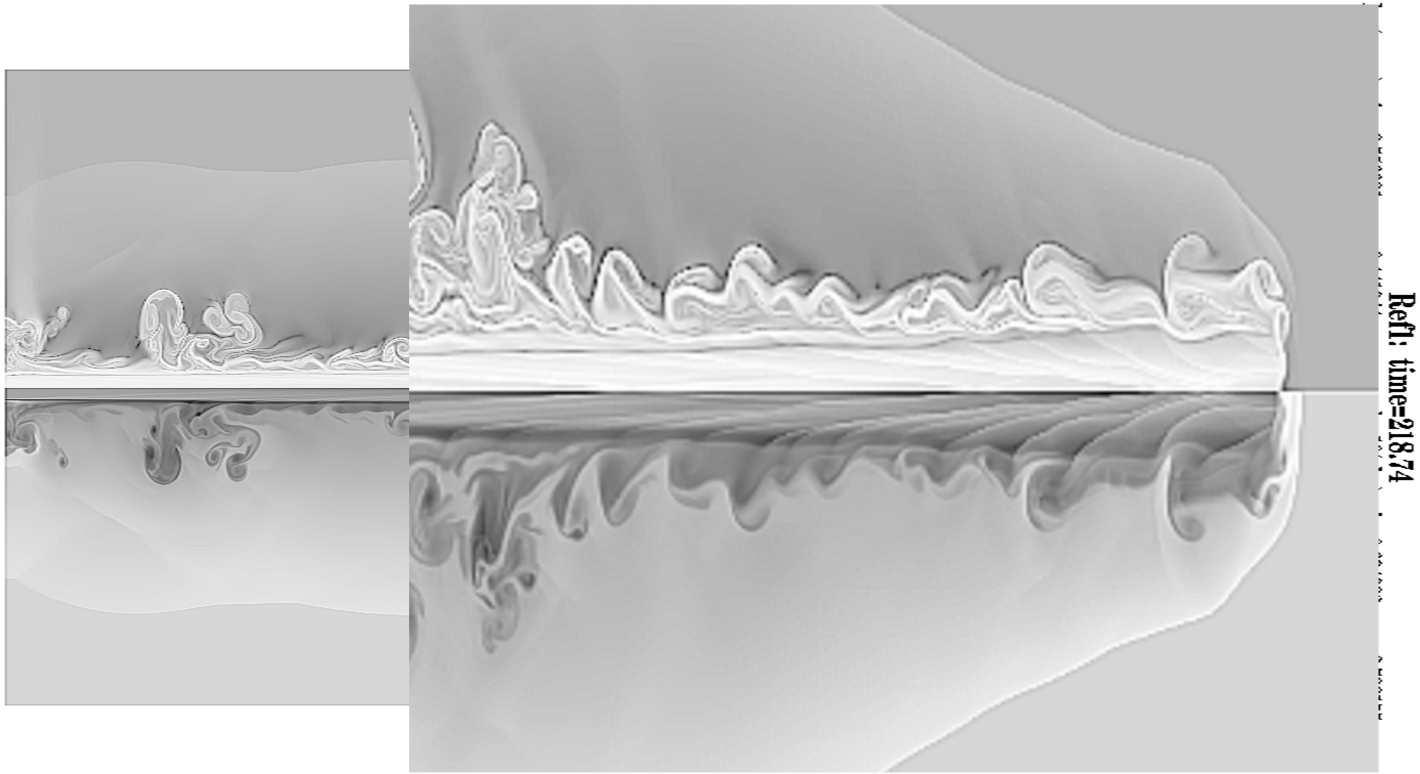
⇛ Helical RMHD jets (i.e. toroidal and poloidal magnetic field) head velocities are typically 'slower' than purely poloidal jets…



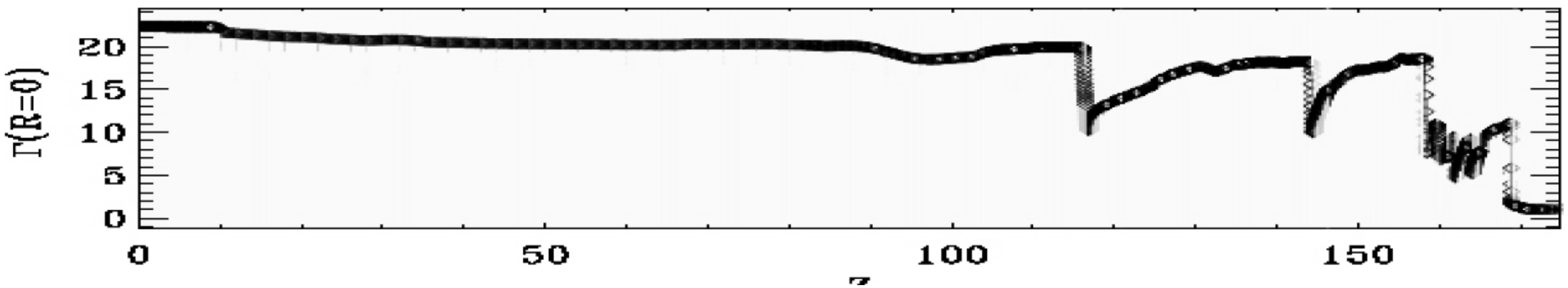
Keppens et al. (2008)

Astrophysical jets propagation : non-relativistic MHD vs relativistic MHD

⇛ Propagation of the jet creates internal shocks.

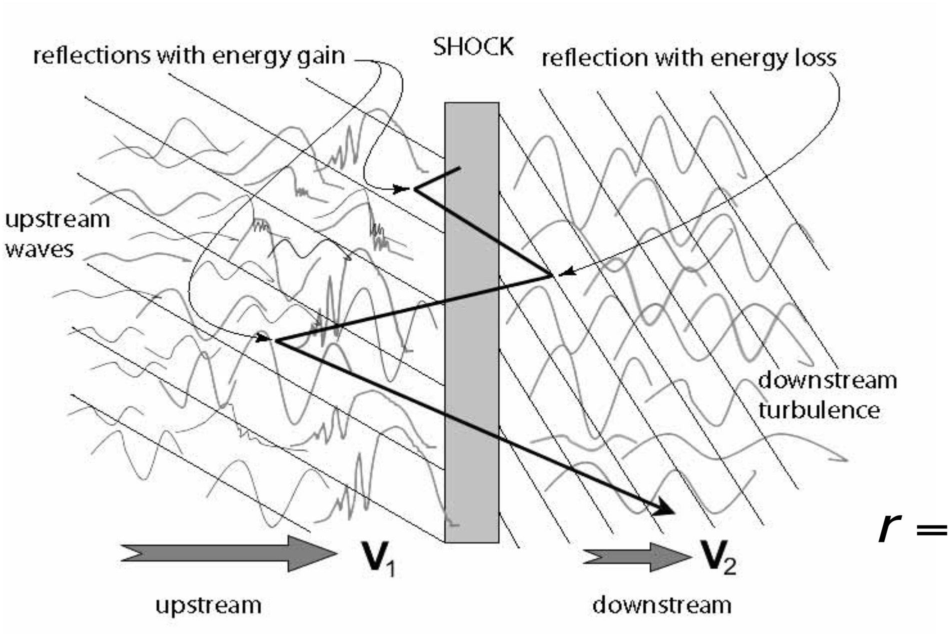


RMHD jet (Γ_{bulk}~8)

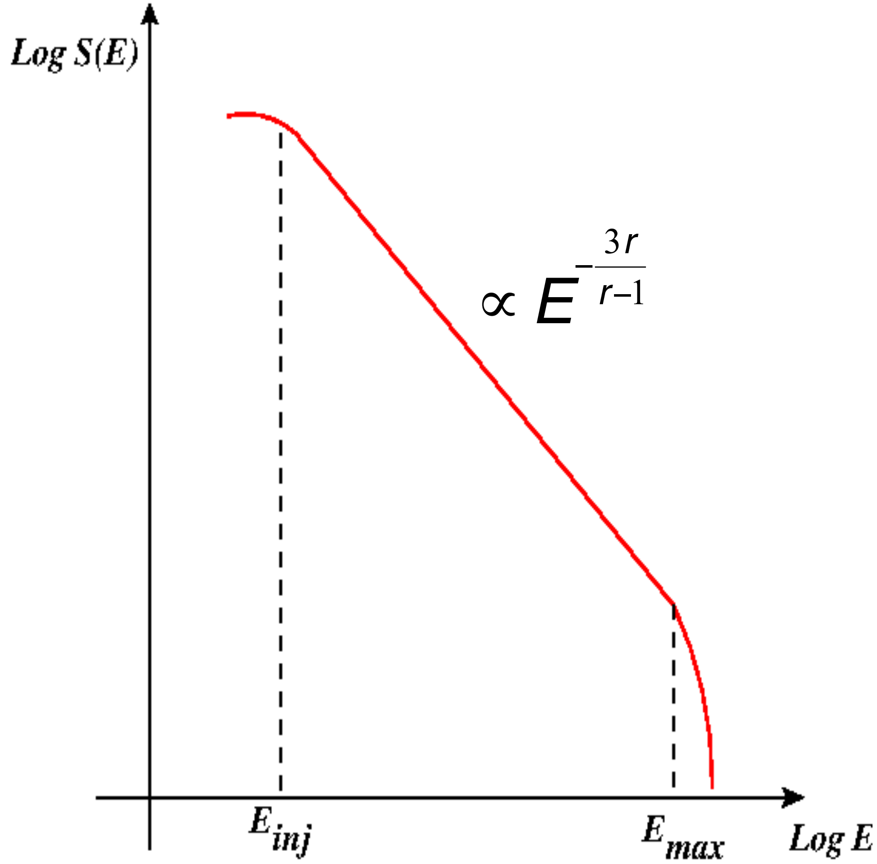


Keppens et al. (2008)

The Diffusive Shock Acceleration (DSA)



$$r = \frac{\rho_d}{\rho_u}$$



- Supra-thermal particles can be accelerated in the vicinity of shock waves.
- DSA acceleration (aka Fermi acc.) consists in multiple crossing of the shock front with a energy gain at each cycle.
- Particle transport properties have a huge influence on the spectrum cut-off E_{max}.

➡ **Magnetic turbulence is a key element to insure particle diffusion.**

Krymsky'77, Axford'77,
Blandford & Ostriker'78, Bell'78

Multi-scale description of DSA

- Describing the DSA of supra-thermal acceleration requires to both take into account the thermal plasma AND the supra-thermal particle population.

  Kinetic theory and MHD are to be considered at once

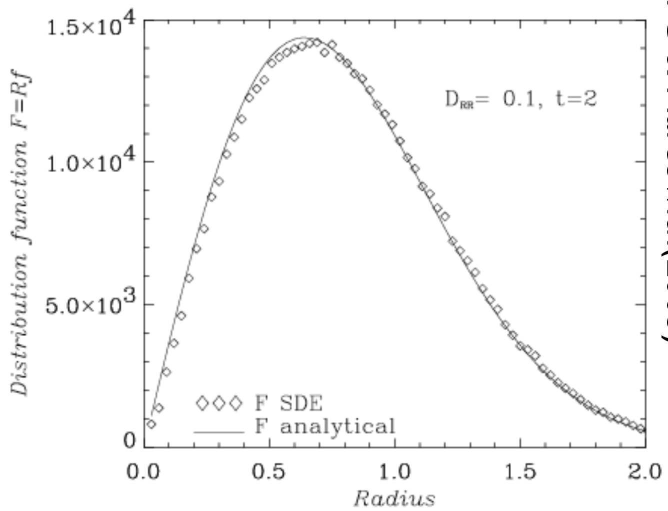
- One way to compute the supra-thermal particle population evolution is to use Stochastic Differential Equations (SDE) to solve the Fokker-Planck equation.

$$\frac{\partial f}{\partial t} = -\sum_{i=1}^{N} \frac{\partial}{\partial X_i}(A_i(t,\boldsymbol{X})f(t,\boldsymbol{X})) + \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} \frac{\partial^2}{\partial X_i \partial X_j}\left(\sum_{k=1}^{N} B_{ik}(t,\boldsymbol{X})B^T_{k,j}(t,\boldsymbol{X})f(t,\boldsymbol{X})\right)$$

Itô(1951)

$$\frac{dX_i}{dt} = A_i(t,\boldsymbol{X}) + \sum_{j=1}^{N} B_{ij}(t,\boldsymbol{X})\frac{dW_j}{dt}$$

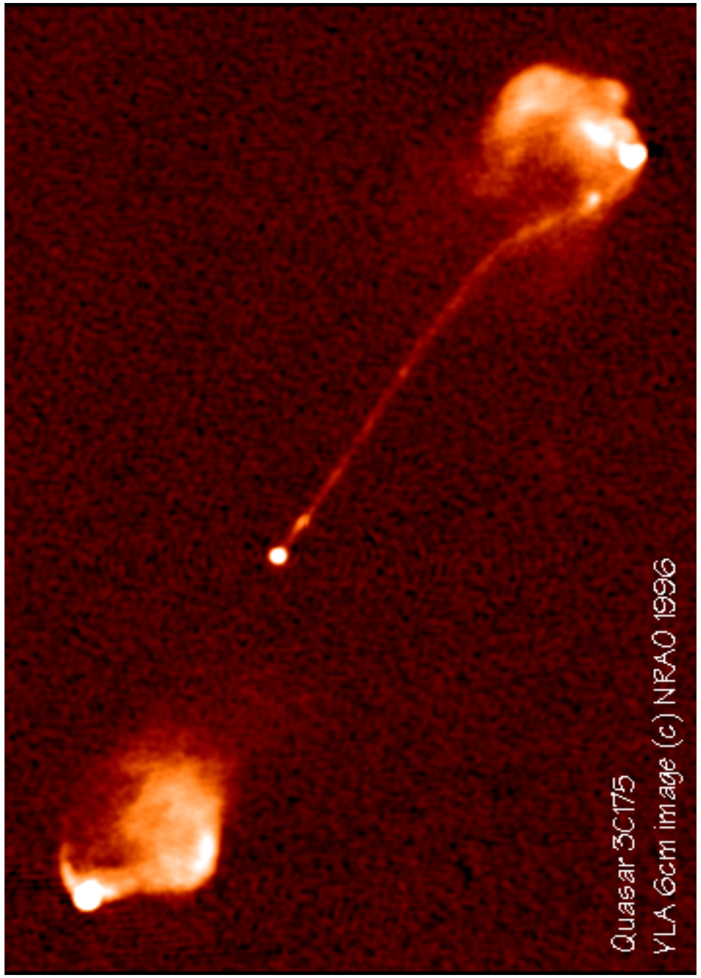
Wiener process = Monte-Carlo

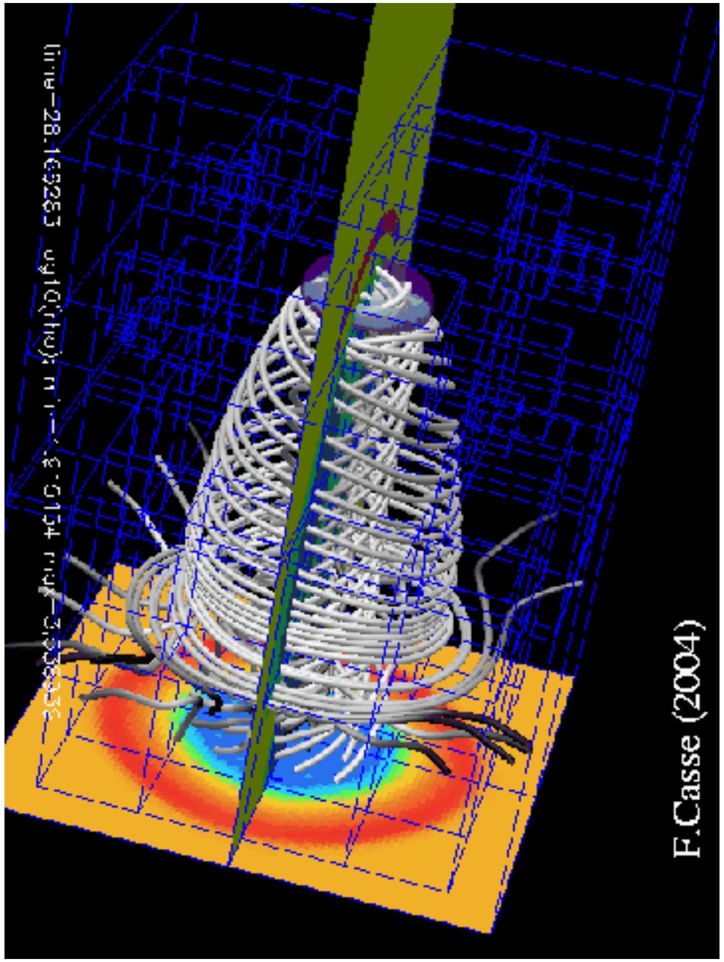


FC & Marcowith(2003)

Applications of MHD-SDE: AGN Hotspots

FC & Marcowith (2005)

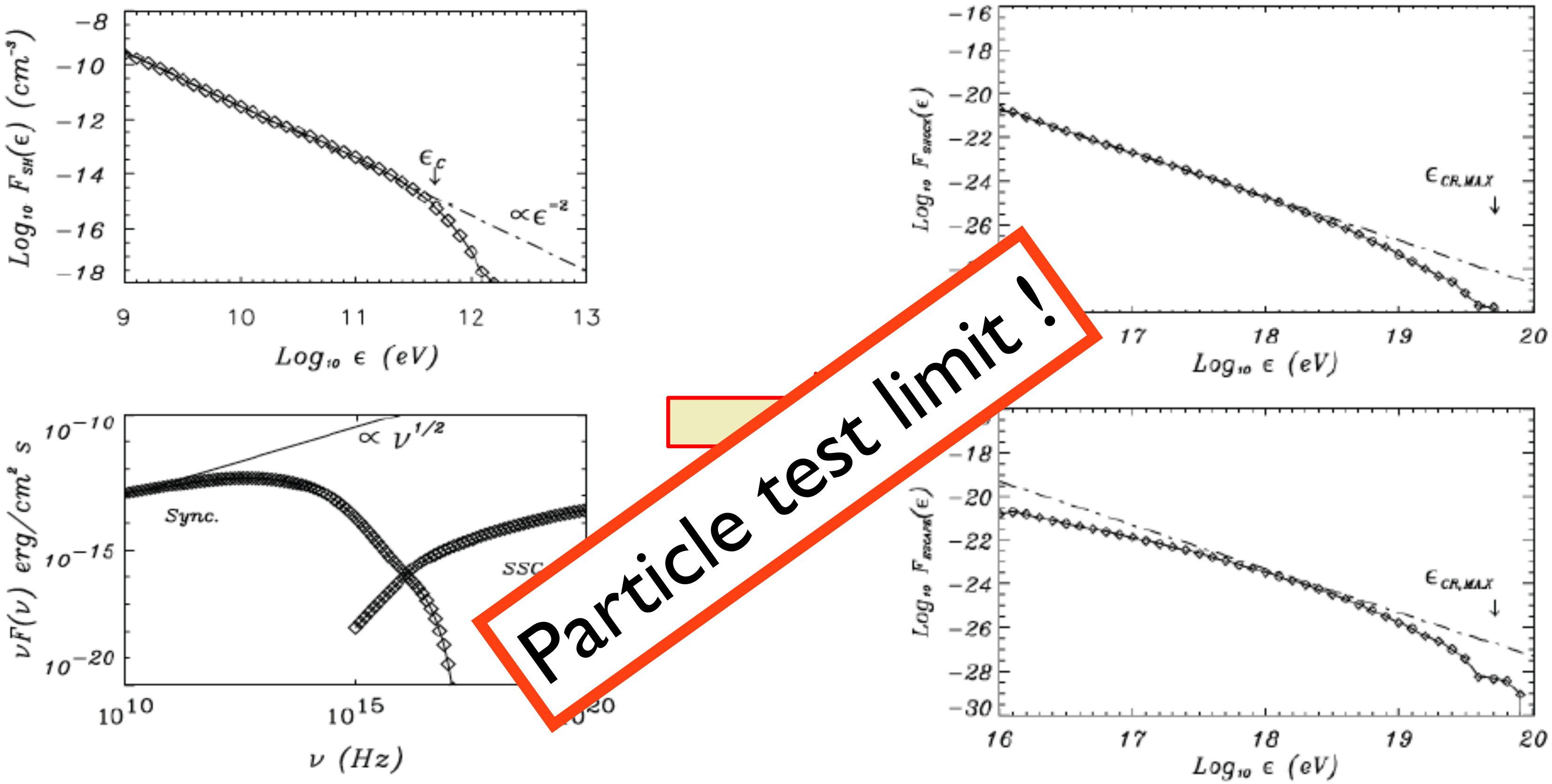




- FR2 Hotpots are one the biggest shock fronts in the Universe
  → so one of the best candidates for UHECR ..

Applications of MHD-SDE: AGN Hotspots

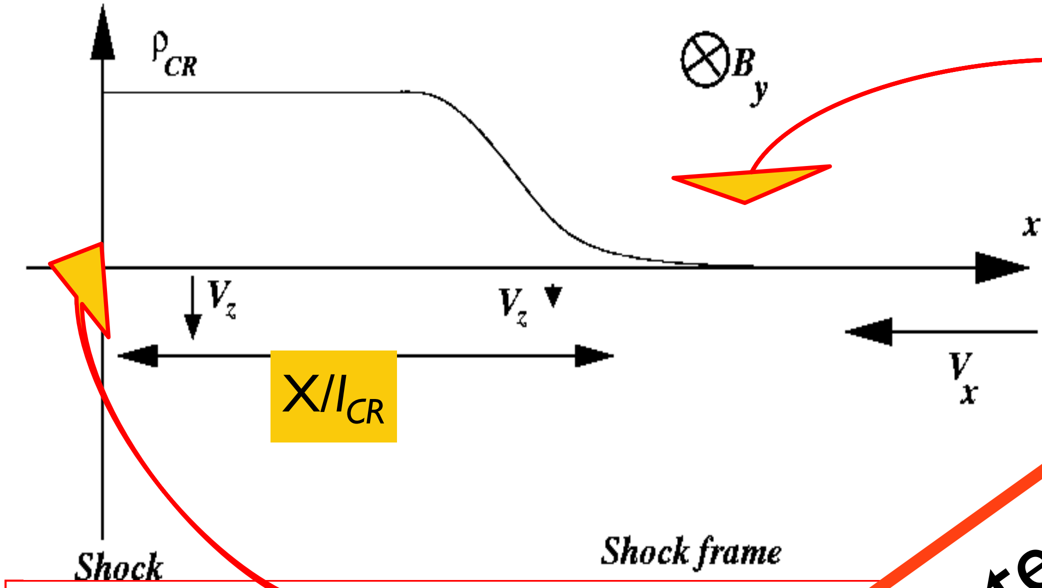
FC & Marcowith (2005)

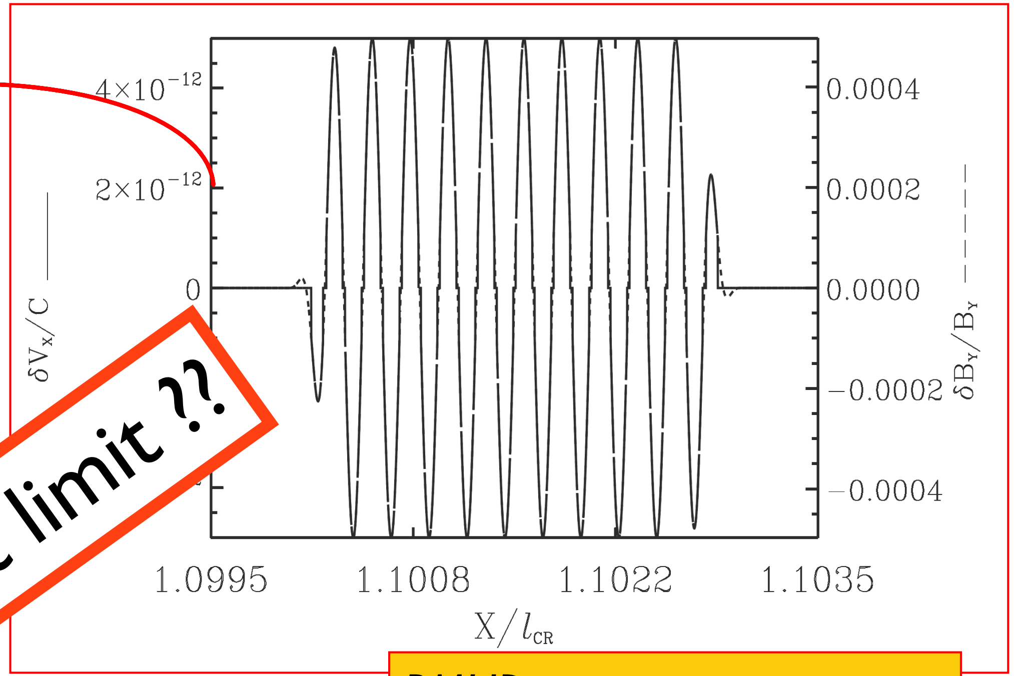


Electrons   Cosmic Rays

- Parameters of the simulation is constrained by observational data.
- Among a sample of 6 HS, only one is found capable of producing UHECR thanks to its perpendicular shock configuration (3C273A).

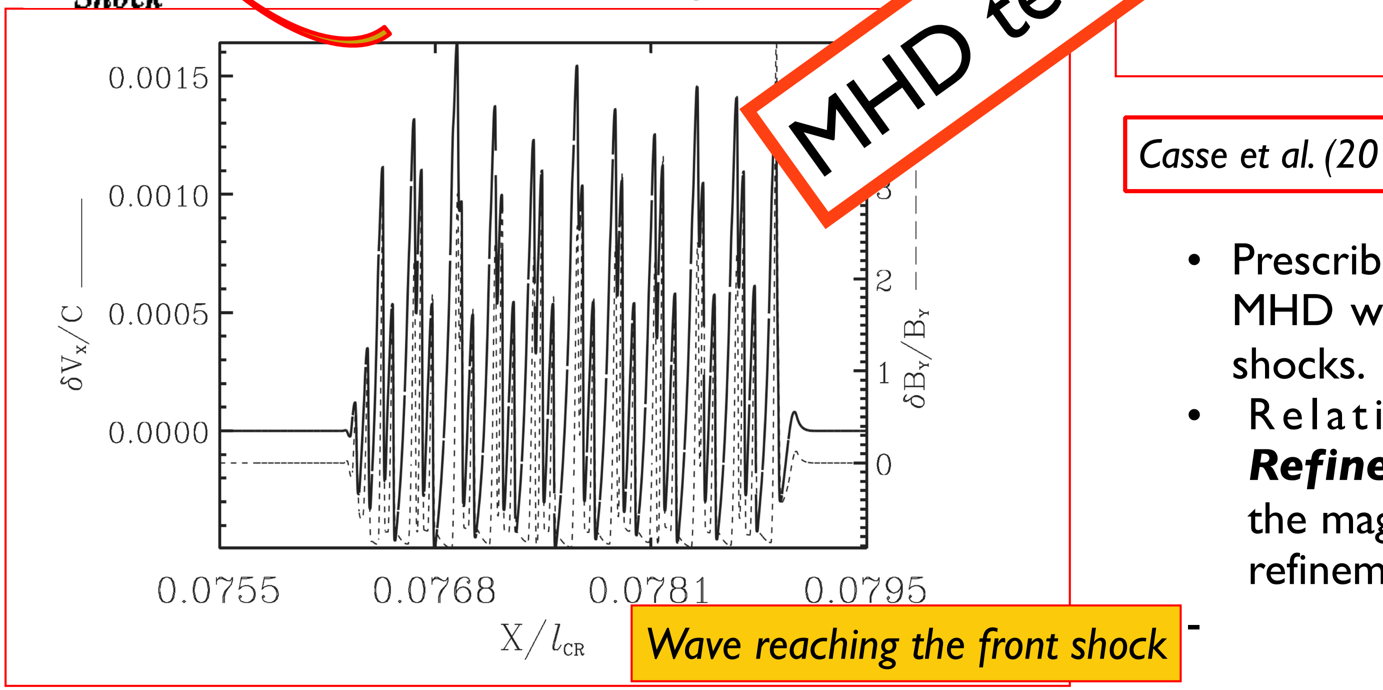
Non-resonant CR streaming instability near relativistic shocks





RMHD wave entering precursor

Casse et al. (2013)

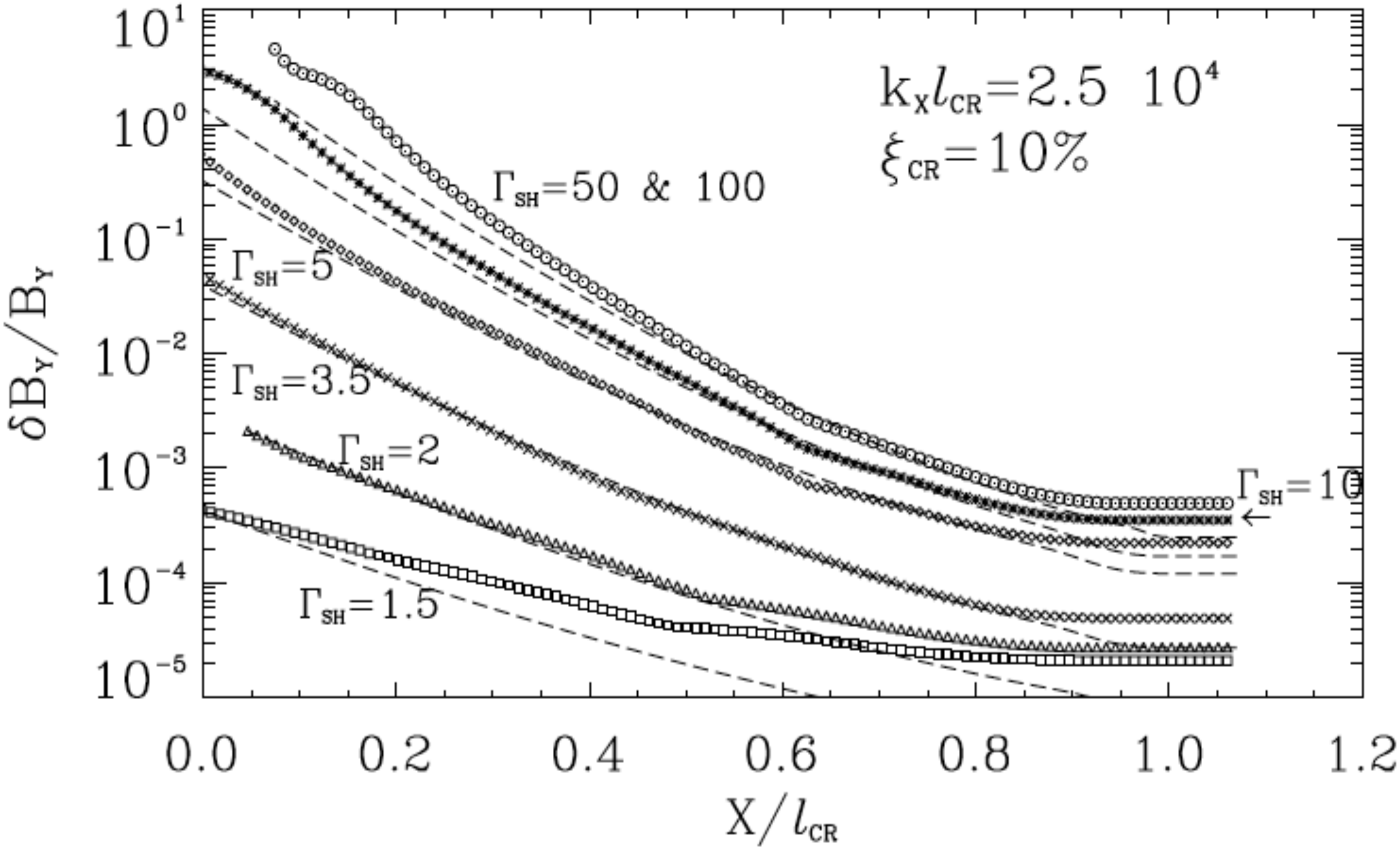


Wave reaching the front shock

- Prescribed CR electric charge destabilized MHD waves in precursor of ultra relativistic shocks.
- Relativistic ***Adapatative Mesh Refinement*** MHD simulations describes the magnetic perturbation growth (up to 12 refinement levels).

Non-resonant CR streaming instability near relativistic shocks

Casse et al. (2013)

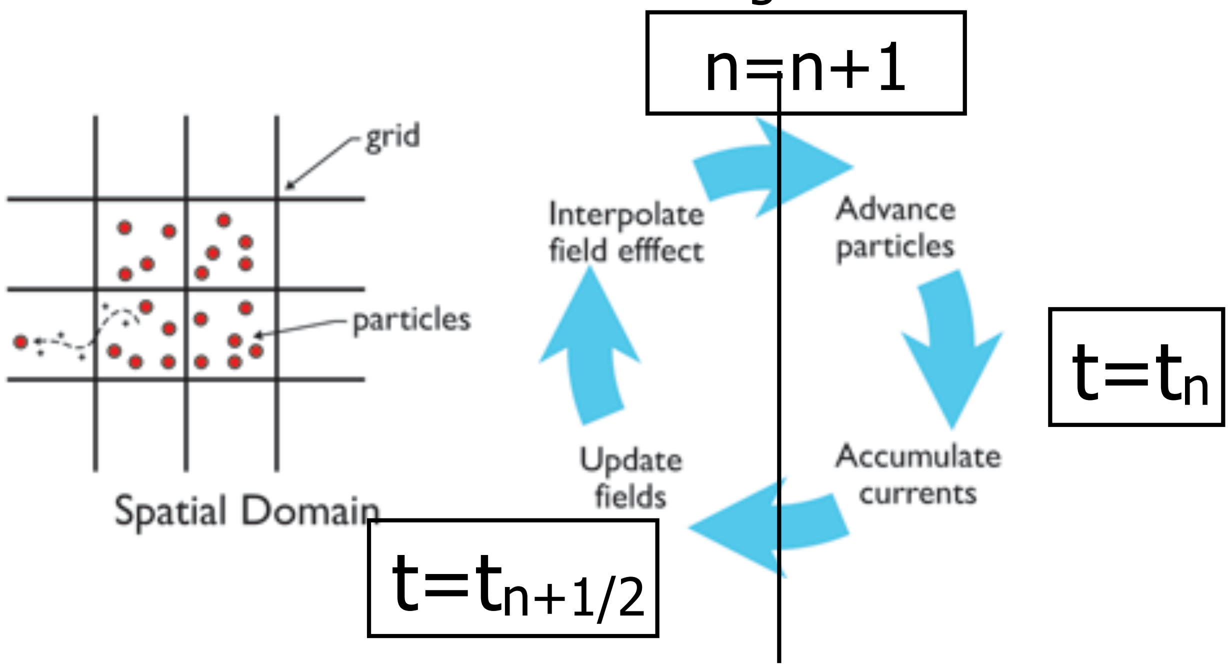


Particles-In-Cell (PIC) simulations

➡ PIC simulations are based on the interaction between charged particles moving into an electromagnetic field.

- Particles are prone to the Lorentz force
- Electromagnetic field is influenced by the motion of particles as they provide space and time dependent electric charge and current densities.

➡ Electromagnetic field is time advanced on a grid and Lorentz force is interpolated from the closest vertices of the grid.



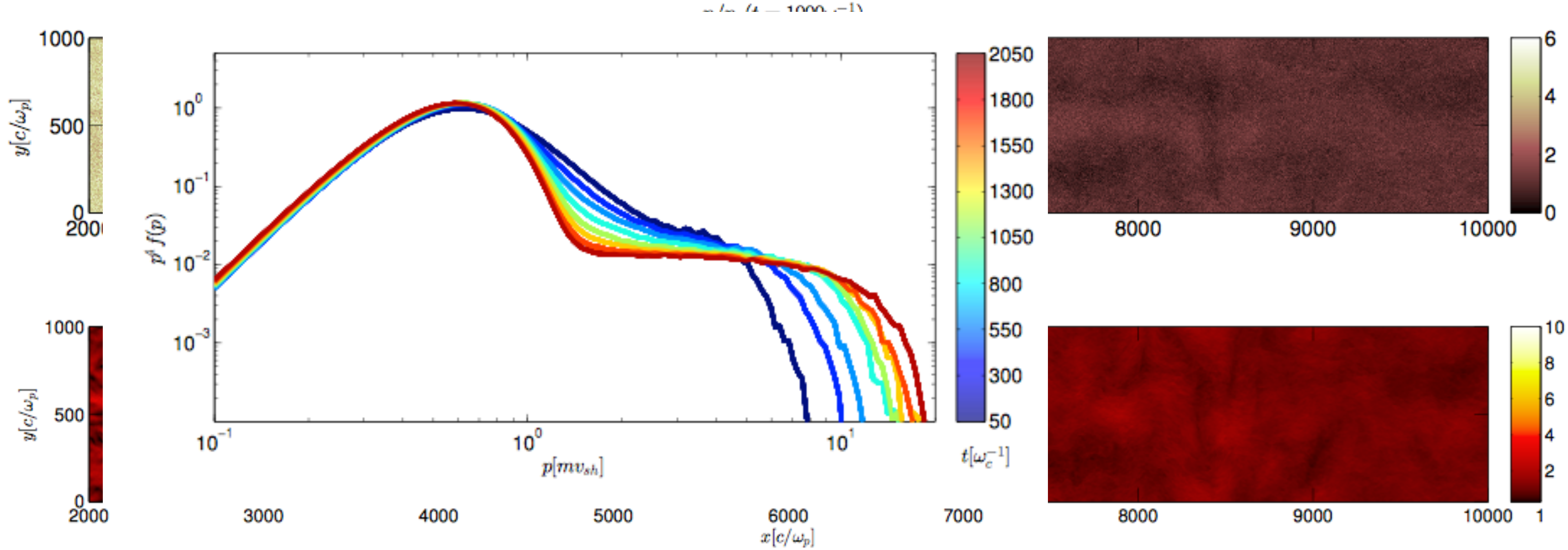
PIC simulations: Diffusive shock acceleration

- Since Spitkovsky (2008), PIC codes have been proven capable to capture the Fermi acceleration process together with the magnetic field amplification.

- Unfortunately PIC simulations only depict the beginning of the process (magnetic amplification + supra-thermal particles production, e.g. Caprioli & Spitkovsky 2014) because of <u>computational limitations</u>…

- The longest PIC run covers less than 1% of the acceleration region (Keshet et al. 2009).

An alternative approach has to be considered …



MHD including ‘cosmic rays’

➡ Taking into account supra-thermal particles into a thermal plasma modifies the Ohm’s law as now the thermal plasma is no longer neutral and the total current has to take into account the supra-thermal current

$$n_e q_e (\vec{\mathbf{E}} + \vec{\mathbf{U}}_e \times \vec{\mathbf{B}}) = \vec{\nabla} P_e \;\Rightarrow\; \vec{\mathbf{E}} = -\vec{\mathbf{U}} \times \vec{\mathbf{B}} - \cancel{\frac{\vec{\mathbf{J}}_{TOT} \times \vec{\mathbf{B}}}{n_e q_e}} + \frac{n_{CR}}{n_e}(\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}} + \cancel{\frac{\vec{\nabla} P_e}{n_e q_e}}$$

where

$$n_e q_e + n_i q_i + n_{CR} q_i = 0$$

$$\vec{\mathbf{J}}_{TOT} = \vec{\mathbf{J}}_{PL} + \vec{\mathbf{J}}_{CR} = n_e q_e \vec{\mathbf{U}}_e + n_i q_i \vec{\mathbf{U}}_i + n_{CR} q_i \vec{\mathbf{U}}_{CR}$$

➡ One can safely neglect thermal electron pressure gradient because of usual MHD ordering provided that the magnetic field <u>is not much smaller</u> than equipartition (Bai et al. 2015).

➡ The Hall term is significant on scales smaller than **c/ω_{pi}** ..

$$\vec{\mathbf{E}} = -\left((1-\Theta)\vec{\mathbf{U}} + \Theta \vec{\mathbf{U}}_{CR}\right) \times \vec{\mathbf{B}}$$

$$\Theta = \frac{\rho_{CR}}{|\rho_e|} = \frac{\rho_{CR}}{\rho_i + \rho_{CR}}$$

MHD including 'cosmic rays'

➡ RMHD momentum conservation reads

$$\frac{\partial \gamma^2 \rho h \vec{\mathbf{U}}}{\partial t} + \vec{\nabla}.(\gamma^2 \rho h \vec{\mathbf{U}}\vec{\mathbf{U}} + P\vec{\vec{1}}) = -\rho_{CR}\vec{\mathbf{E}} + (\vec{\mathbf{J}}_{TOT} - \vec{\mathbf{J}}_{CR}) \times \vec{\mathbf{B}}$$

➡In classical MHD, the momentum equation is modified by the presence of a source term accounting for the streaming of CR:

$$\frac{\partial \rho \vec{\mathbf{U}}}{\partial t} + \vec{\nabla}.\left(\rho \vec{\mathbf{U}}\vec{\mathbf{U}} - \frac{\vec{\mathbf{B}}\vec{\mathbf{B}}}{\mu_o} + P_{TOT}\vec{\vec{1}}\right) = (1-\Theta)\{\rho_{CR}(\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}}\}$$

➡ In RMHD framework the displacement current has to be taken into account so one needs to reconsider the definition of RMHD conservative variables

$$\frac{\partial}{\partial t}\{\gamma^2 \rho h \vec{\mathbf{U}} + \vec{\mathbf{E}} \times \vec{\mathbf{B}}\} + \vec{\nabla}.\left\{[\gamma^2 \rho h]\vec{\mathbf{U}}\vec{\mathbf{U}} - \vec{\mathbf{B}}\vec{\mathbf{B}} - \vec{\mathbf{E}}\vec{\mathbf{E}} + \left(P + \frac{B^2 + E^2}{2}\right)\vec{\vec{1}}\right\}$$
$$= \rho_{CR}(1-\Theta)(\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}}$$

$$\vec{\mathbf{E}} = -((1-\Theta)\vec{\mathbf{U}} + \Theta\vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}}$$

PMHDC simulations

➡**Particles in MHD Cells** (PMHDC) simulations rely on

- the MHD description to time-advanced both the electromagnetic field and thermal plasma mass density, velocity and energy.
- The PIC description to time-advanced the position and velocity of supra-thermal particles.

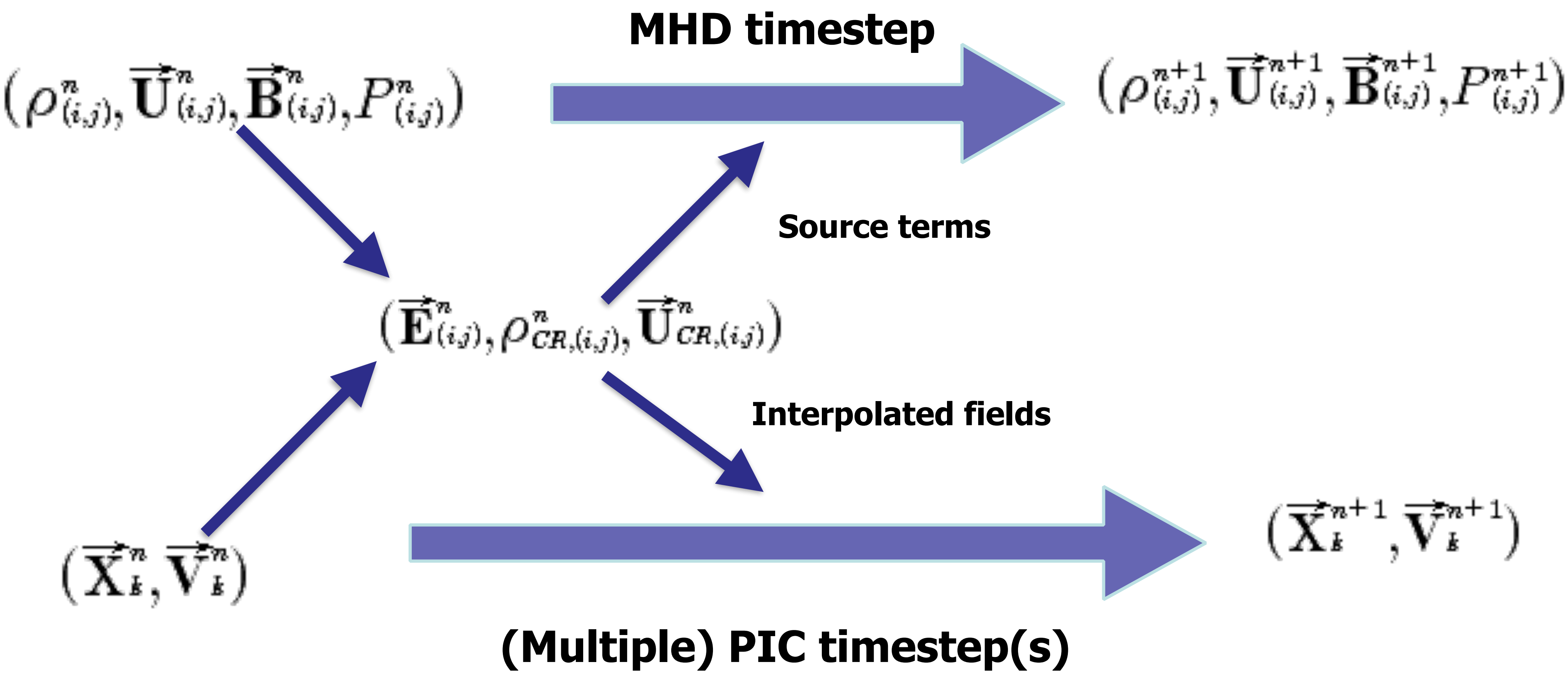
➡The PIC motion equations related to the particles are also modified according to the new Ohm's law (neglecting thermal electron pressure and Hall effect)

$$\frac{d\gamma\vec{v}_k}{dt} = \frac{q_k}{m_k}\left\{(\Theta - 1)\vec{\mathbf{U}} - \Theta\vec{\mathbf{U}}_{CR} + \vec{v}_k\right\} \times \vec{\mathbf{B}}$$

$$\sum_k \frac{m_k}{V_{cell}}\frac{d\gamma\vec{v}_k}{dt} = -(1-\Theta)\left\{\rho_{CR}(\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}) \times \vec{\mathbf{B}}\right\}$$

$$\sum_k \frac{m_k}{V_{cell}}\vec{v}_k.\frac{d\gamma\vec{v}_k}{dt} = (1-\Theta)\vec{\mathbf{J}}_{CR}.(-\vec{\mathbf{U}} \times \vec{\mathbf{B}}) = -\vec{\mathbf{U}}.\begin{pmatrix} \frac{\partial}{\partial t}\left\{\vec{\mathbf{S}} + \Theta\left[((\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR}).\vec{\mathbf{B}})\vec{\mathbf{B}} - (\vec{\mathbf{U}} - \vec{\mathbf{U}}_{CR})B^2\right]\right\} \\ +\vec{\nabla}.\left\{\vec{\mathbf{S}}\vec{\mathbf{U}} - \left(\frac{\vec{\mathbf{B}}}{\gamma^2} + (\vec{\mathbf{U}}.\vec{\mathbf{B}})\vec{\mathbf{U}}\right)\vec{\mathbf{B}} + P_{TOT}\,\vec{1}\right\} \end{pmatrix}$$

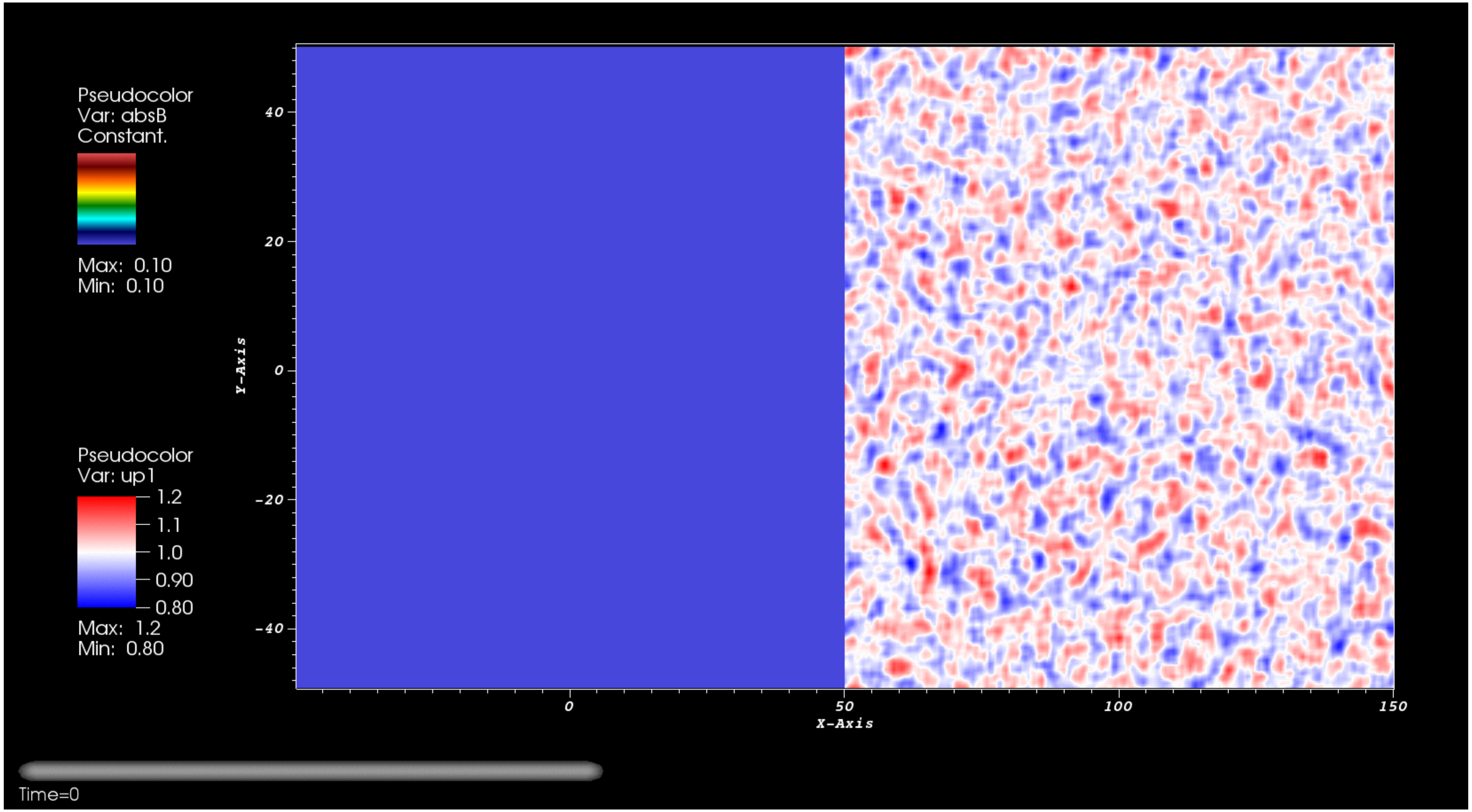
Basics of Particle in MHD Cells simulations



Preliminary Particle in MHD Cells simulations

➡ Here is an example of the effect of the streaming of particle through a magnetized plasma (ongoing work)...

➡ PI(MHD)C code developed from the MPI-AMRVAC code (Keppens et al. 2012)



VanMarle & Casse

Outlook

ANR MACH project:
IAP(M. Lemoine) - LUPM (A. Marcowith)- IPAG(G. Pelletier) - APC(FC, A.J. Van Marle),
CELIA (V. Tikhonchuk, E. D'Humières)- CEA/DAM(L. Gremillet)

- Particle in (R)MHD Cells is a promising tool to describe particle acceleration *and* MHD turbulence at once over a large distance.

- One of the main goals of this new code is to develop state-of-art PI(RMHD)C with full MPI parallelization and *adaptative mesh refinement*.

- We plan to study acceleration of particles in all shock velocity regimes (from non-relativistic to ultra-relativistic).

- This formalism can be applied on any kind of environment where thermal plasma harbors supra-thermal particle

- Limitation ? —> Very small scale fluctuations cannot be addressed…